Chapter 6

Mechanical Properties of Metals

Mechanical Properties refers to the behavior of material when external forces are applied

Stress and strain ⇒ fracture

For engineering point of view: allows to predict the ability of a component or a structure to withstand the forces applied to it

For science point of view: what makes materials strong → helps us to design a better new one

Learn basic concepts for metals, which have the simplest behavior

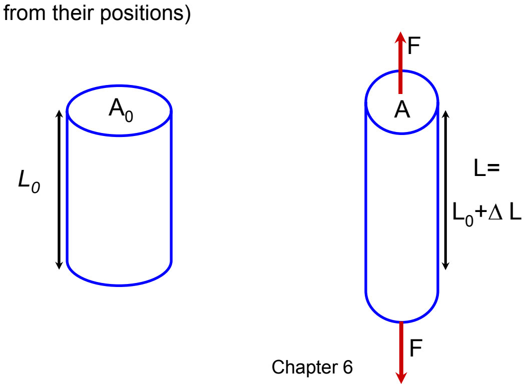
Return to it later when we study ceramics, polymers, composite materials, nanotubes

6.1 Elastic and Plastic Deformation

- Metal piece is subjected to a uniaxial force ⇒ deformation occurs
- When force is removed:

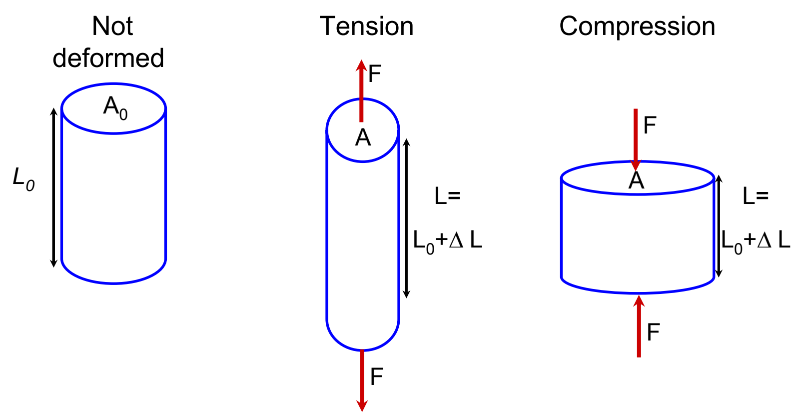
  - metal returns to its original dimensions ⇒ **elastic** deformation (atoms return to their *original position*)

  - metal deformed to an extent that it cannot fully recover its original dimensions ⇒ **plastic** deformation (shape of the material changes, atoms are *permanently displaced* from their positions)



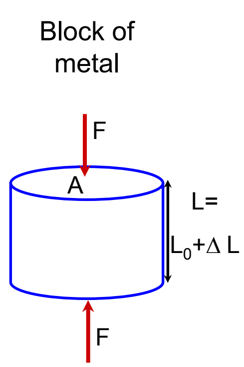
6.2 Concept of Stress and Strain

Load can be applied to the material by applying axial forces:



ΔL can be measured as a function of the applied force; area A_0 changes in response

Stress (σ) and Strain (ε)



Stress (σ)

- defining F is not enough (F and A can vary)
- Stress σ stays constant

$$\sigma = \frac{F}{A}$$

- Units

  Force / area = N / m^2 = Pa

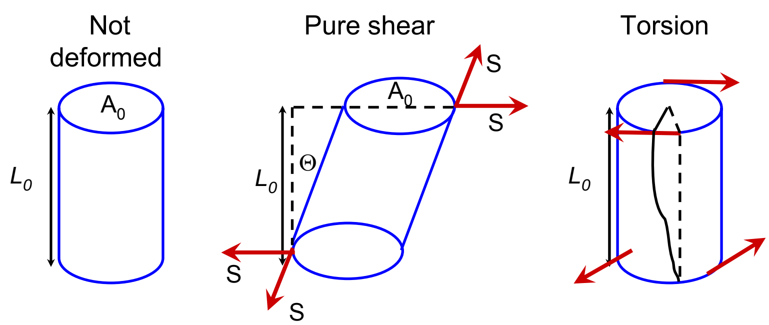
  usually in MPa or GPa

Strain (ε) – result of stress

- For tension and compression: change in length of a sample divided by the **original** length of sample

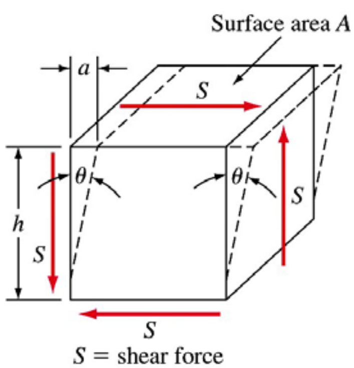
$$\varepsilon = \frac{\Delta L}{L}$$

Shear and Torsion (similar to shear)



- Note: the forces are applied in this way, so that there is no net torque
- If the forces are applied **along** the faces of the material, they are called shear forces

Shear Stress and Shear Strain



If the shear force S acts over an area A, the shear stress τ:

$$\tau(shear\_stress) = \frac{S(shear\_force)}{A(area)}$$

The shear strain γ is defined in terms of the amount of the shear displacement a divided by distance over which the shear acts:

$$\gamma = \frac{a}{h} = \tan\Theta$$

Elastic Properties of Materials

- Most materials will get narrow when stretched and thicken when compressed
- This behaviour is qualified by Poisson's ratio, which is defined as the ratio of ***lateral*** and ***axial*** strain

$$Poisson's\_Ratio: \nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

• the minus sign is there because usually if $\varepsilon_z > 0$, and $\varepsilon_x + \varepsilon_y < 0 \Rightarrow \nu > 0$

• It can be proven that we must have $\nu \leq ½$; $\nu = ½$ is the case when there is no volume change

$$(l_x + \Delta l_x)(l_y + \Delta l_y)(l_z + \Delta l_z) = l_x \times l_y \times l_z$$

Poisson's Ratio, ν

• For **isotropic materials** (i.e. material composed of many randomly - oriented grains) $\nu = 0.25$

• For most metals:

$$0.25 < \nu < 0.35$$

• If $\nu = 0$:means that the width of the material doesn't change when it is stretched or compressed

• Can be:

$$\nu < 0$$

(i.e. the material gets thicker when stretched)

6.3 Modulus of elasticity, or Young's Modulus

- Stress and strain are properties that don't depend on the dimensions of the material (for small ε), just type of the material

$$E = \frac{\sigma(stress)}{\varepsilon(strain)}$$

- E – Young's Modulus, Pa
- Comes from the linear range in the stress-strain diagram
- many exceptions…

Behavior is related to **atomic bonding between the atoms**

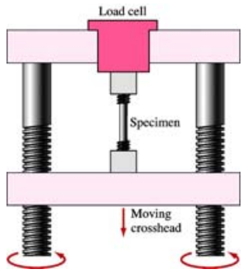
Material	Young's Modulus [GPa]
Metals	20-100
Polypropelene	1.5-2
Rubber	0.01
Hydrogels and live cells	<0.00001

Q.: A wagon of mass m = 1100kg is suspended from the bridge by a steel cable of d = 1cm and length L = 10m. E(steel) = 2×10^{11}Pa

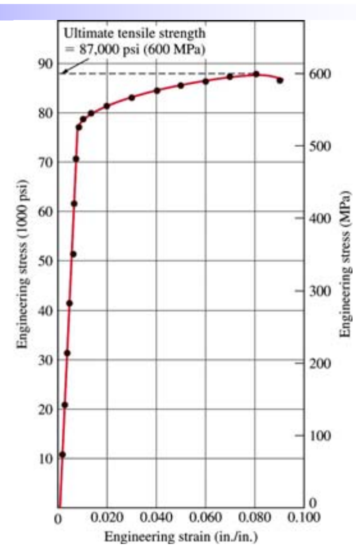
(a) By how much will the cable stretch?

(b) Can the cable handle this?

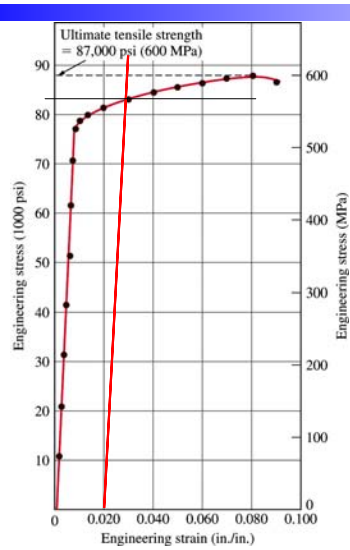
Tensile Test



1. Modulus of elasticity
2. Yield strength at 0.2% offset
3. Ultimate tensile strength
4. Percent elongation at fracture
5. Percent reduction in area at fracture

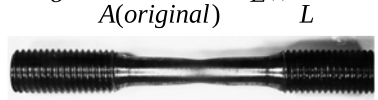


Other tensile test characteristics:



- **Yield strength** (at 0.2% offset)
- **Ultimate Tensile Strength** (UTS): the maximum strength reached in the stress-strain curve

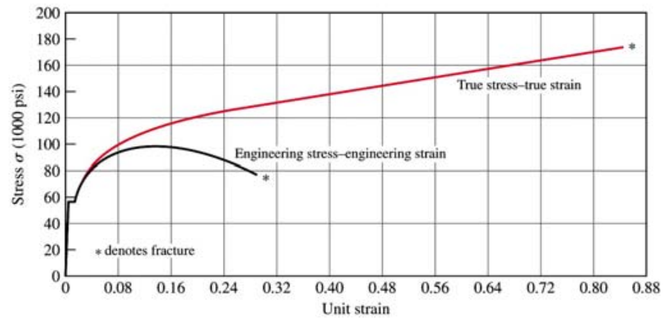
$$\sigma = \frac{F}{A(original)} = E \times \frac{\Delta L}{L}$$



- Percent elongation at fracture (measure of **ductility** of the metal)
- Percent reduction in area at fracture

$$\%\_reduction\_in\_area = \frac{A_{initial} - A_{final}}{A_{initial}} \times 100\%$$

True and Engineering Stress



$$\sigma_{engineering} = \frac{F}{A_{initial}} = E \times \frac{\Delta L}{L}$$

$$\sigma_{true} = \frac{F}{A_{instant}}$$

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6.4 Hardness

Hardness: a measure of the resistance of a material to plastic (permanent) deformation

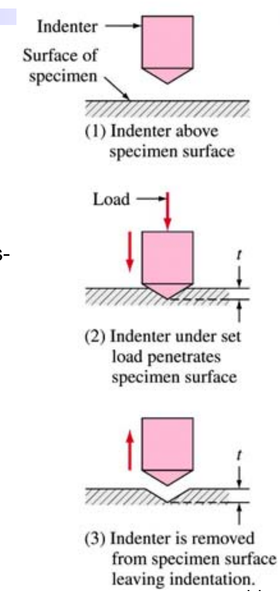
Measured by **indentation**

- indenter material (ball, pyramid, cone) is harder than the material being tested (i.e.: tungsten carbide, diamond)
- indenter is pressed at 90°
- hardness is based on the depth of the impression or its cross-sectional area

Several common hardness tests: **hardness numbers** can be calculated

Material strength and hardness are related

Hardness test is nondestructive ⇒ often used



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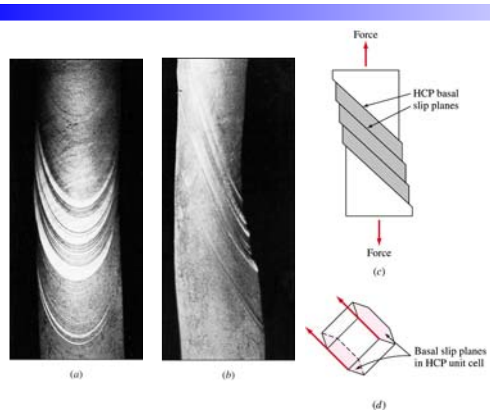
Hardness tests: hardness numbers

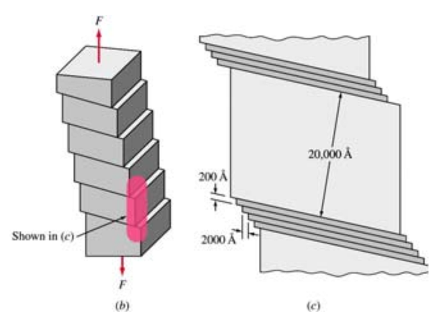
Table 6.2 Hardness tests

Test	Indenter	Shape of indentation: Side view	Shape of indentation: Top view	Load	Formula for hardness number
Brinell	10 mm sphere of steel or tungsten carbide	D, d	d	P	$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid	136°	d_1, d_1	P	$VHN = \frac{1.72P}{d_1^2}$
Knoop microhardness	Diamond pyramid	t; $l/b = 7.11$, $b/t = 4.00$	b, l	P	$KHN = \frac{14.2P}{l^2}$
Rockwell A, C, D	Diamond cone	120°, t		60 kg, 150 kg, 100 kg	$R_A =$, $R_C =$, $R_D =$ 100–500f
B, F, G	$\frac{1}{16}$-in.-diameter steel sphere			100 kg, 60 kg, 150 kg, 100 kg	$R_B =$, $R_F =$, $R_G =$, $R_E =$ 130–500f
E	$\frac{1}{8}$-in.-diameter steel sphere	t			

Source: After H. W. Hayden, W. G. Moffatt, and J. Wulff, "The Structure and Properties of Materials," vol. III, Wiley, 1965, p. 12.

6.5 Plastic deformations of single crystal metals





A rod of a single crystal **Zn (hcp)** stressed beyond its elastic limit:

- slipbands: slip of metal atoms on specific crystallographic planes (*slip planes*)
- slip is **predominately** along the *basal planes*

A rod of a single crystal **Cu (fcc)** during plastic deformation:

- slip lines: 50-500 atoms apart
- slipbands: separated by ~>10,000 atomic planes

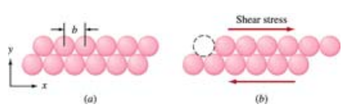
Other mechanical characteristics

- **Ductility**: amount of plastic deformation that occurs before fracture
  - if ductility is high, the material can be deformed by applying stresses.
    Ex.: gold
  - if it is low, material breaks first, without significant deformation (material is brittle)
  - depend on T: at low T many metals become brittle and can break as a glass

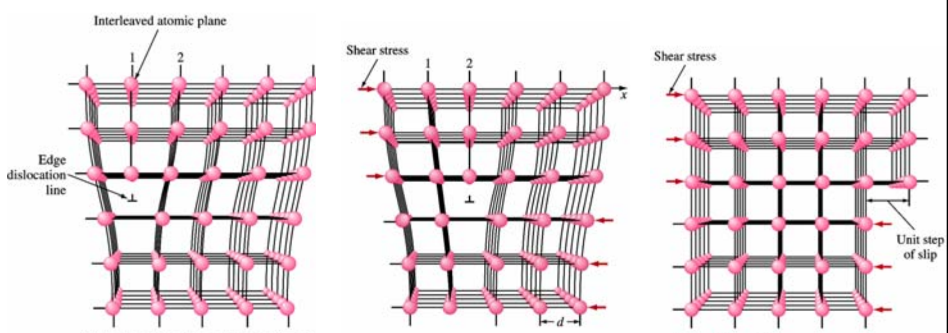
- **Resilience**: ability to have high yield strength and low E.
  Ex.: good springs

- **Toughness**: ability to absorb energy up to a fracture

Mechanism of Slip deformation



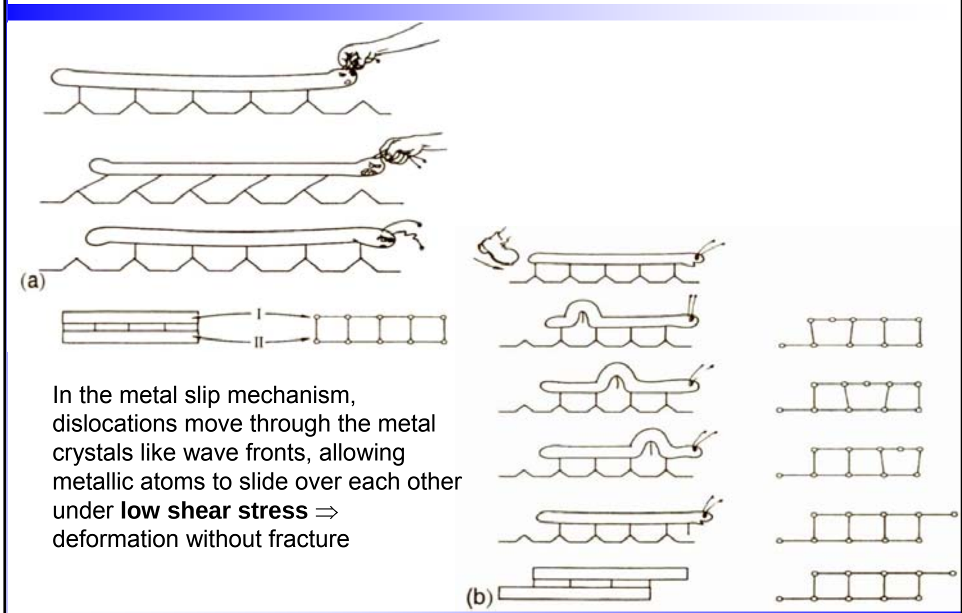
the group of atoms do NOT slide over each other during plastic shear deformation ⇒ the process requires too much energy



(a) An edge dislocation, pictured as formed by an extra half plane of atoms. (b) A low stress causes a shift of atomic bonds to free a new interleaved plane. (c) Repetition of this process causes the dislocation to move across the crystal.

The process takes less energy!!!

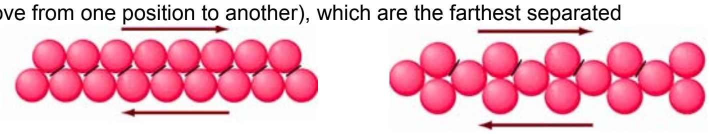
Motion of Dislocations



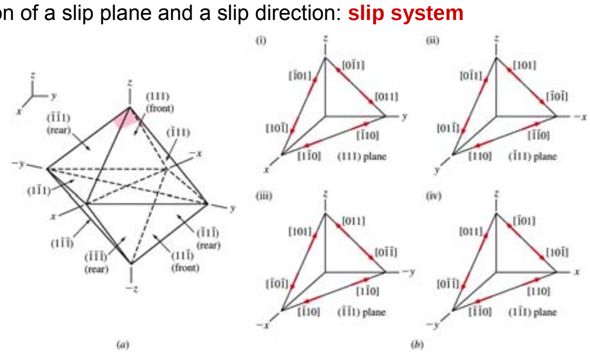
In the metal slip mechanism, dislocations move through the metal crystals like wave fronts, allowing metallic atoms to slide over each other under **low shear stress** ⇒ deformation without fracture

Slip Systems

Typically slip planes are the most densely packed planes (less energy is required to move from one position to another), which are the farthest separated

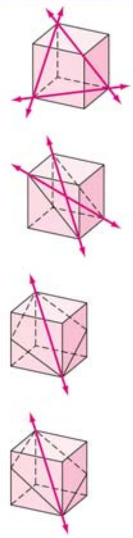


Combination of a slip plane and a slip direction: **slip system**



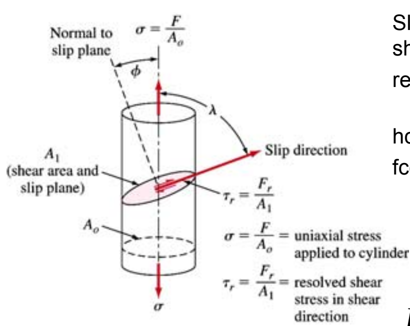
Slip systems observed in crystal structures

Structure	Slip plane	Slip direction	Number of slip systems
FCC: Cu, Al, Ni, Pb, Au, Ag, γFe, . . .	{111}	$\langle 1\bar{1}0 \rangle$	4 × 3 = 12
BCC: αFe, W, Mo, β brass	{110}	$\langle \bar{1}11 \rangle$	6 × 2 = 12
αFe, Mo, W, Na	{211}	$\langle \bar{1}11 \rangle$	12 × 1 = 12
αFe, K	{321}	$\langle \bar{1}11 \rangle$	24 × 1 = 24



For **hcp** crystals: 3 slip systems, restricts their ductility

Schmid's Law



Slip process begins within the crystal when the shear stress on the slip plane in slip direction reaches ***critical resolved shear stress*** τ_c

hcp (Zn, Mg): 0.18, 0.77 MPa
fcc (Cu): 0.48 MPa

$$\tau_r = \frac{F_r}{A_{slip\_plane}}$$

$$F_r = F\cos\lambda \qquad A_{slip\_plane} = \frac{A_o}{\cos\phi}$$

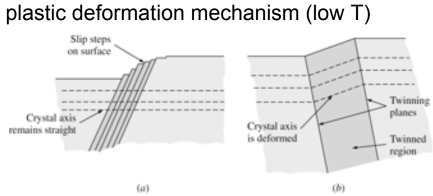
$$\tau_r = \frac{F\cos\lambda\cos\phi}{A_o} = \frac{F}{A_o}\cos\lambda\cos\phi = \sigma\cos\lambda\cos\phi$$ Schmid's law

Q.: A stress of 75 MPa is applied in the [0 01] direction on an *fcc* single crystal.
Calculate

(a) the resolved shear stress acting on the (111) [-101] slip system and,
(b) (b) the resolved shear stress acting on the (111) [-110] slip system.

Mechanical Twinning

Another important plastic deformation mechanism (low T)



Schematic diagram of surfaces of a deformed metal after (a) slip and (b) twinning

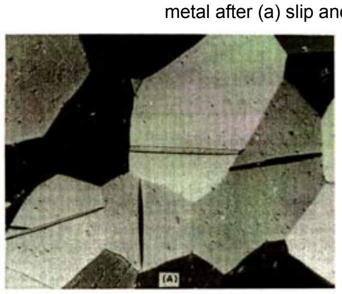


Fig. 6.22. Deformation twins in zirconium.

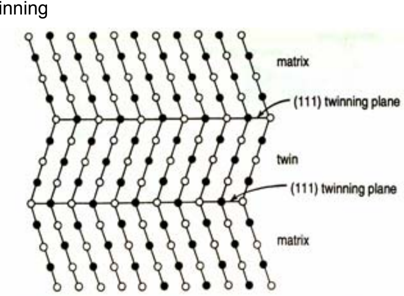
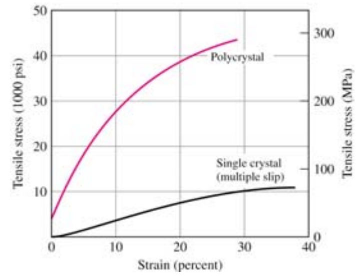


Fig. 6.23. Atomic configuration in matrix and twin of a fcc lattice.

from G. Gottstein

6.6 Plastic Deformations in Polycrystalline Metals

- Majority of engineering alloys and metals are **polycrystalline**
- Grain boundaries – act as diffusion barriers for dislocation movements
- In practice: fine grain materials are stronger and harder (but less resistant to creep and corrosion)



- Strength and grain size are related by *Hall-Pelch equation:*

$$\sigma_y = \sigma_o + \frac{k}{\sqrt{d}}$$

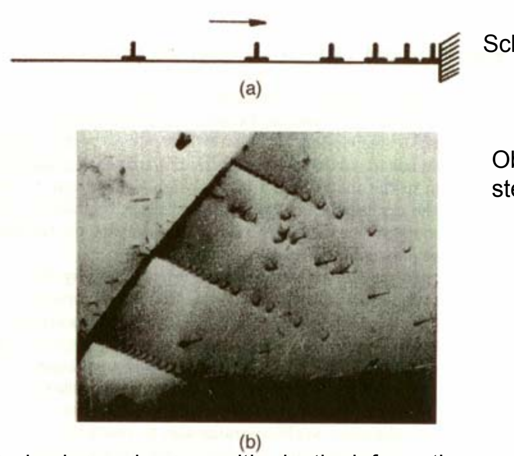
σ_o and k – constants

as grain diameter **decreases**, the yield strength of the material **increases**

Table 6.5 Hall–Petch relationship constants for selected materials

	σ_0 (MPa)	k (MPa · m$^{1/2}$)
Cu	25	0.11
Ti	80	0.40
Mild steel	70	0.74
Ni_3Al	300	1.70

Pile-up of dislocations



Schematic

Observed in stainless steel (TEM)

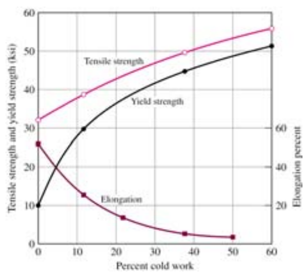
Grain shape changes with plastic deformation

Dislocation arrangement changes

6.7 Cold Plastic Deformation for Strengthening of Metals

- The dislocation density increases with increased cold deformation
- New dislocations are created by the deformation and must interact with those already existing
- As the dislocation density increases with deformation, it becomes more and more difficult for the dislocations to move through the existing dislocations

⇒ Thus the metal work or strain hardens with cold deformation



Percent cold work versus tensile strength and elongation for unalloyed oxygen-free copper

Cold work is expressed as a percent reduction in cross-sectional area of the metal being reduced.

6.8 Superplasticity in Metals

Superplasticity: the ability of some metals to deform plastically by 1000-2000% at high temperature and low loading rates

Ex.: Ti alloy (6Al – 4V)	12%	@ RT, typical tensile test load rates
	~1000%	@ 840ºC, lower loading rates

Requirements:

1. The material must possess very fine grain size (5-10mm) and be highly strain-rate density
2. A high loading T (>0.5 T_m) is required
3. A low and controlled strain rate in the range of 0.01-0.00001 s^{-1} is required

Nanocrystalline Metals

- Nanocrystalline metals: d < 10-50nm

$$\sigma_y = \sigma_o + \frac{k}{\sqrt{d}}$$

- Consider Cu: σ_o = 25 MPa, k = 0.11 MPa $m^{0.5}$ (from Table 6.5)

$$\frac{\sigma_{10nm}}{\sigma_{10\mu m}} = \frac{25MPa + \frac{0.11MPa}{\sqrt{10^{-8}}}}{25MPa + \frac{0.11MPa}{\sqrt{10^{-5}}}} = ?$$

Is this possible?

Different dislocation mechanism: grain boundary sliding, diffusion, etc

Summary

- Introduced stress, strain and modulus of elasticity

$$\sigma = \frac{F}{A} \qquad \varepsilon = \frac{\Delta L}{L} \qquad E = \frac{\sigma(stress)}{\varepsilon(strain)}$$

- Plastic deformations of single crystal metals

- In the single crystal metal - slip mechanism: dislocations move through the metal crystals like wave fronts, allowing metallic atoms to slide over each other under *low shear stress*
- Slip process begins within the crystal when the shear stress on the slip plane in slip direction reaches ***critical resolved shear stress*** τ_c
- *Schmid's law:*

$$\tau_r = \frac{F \cos\lambda \cos\phi}{A_o} = \frac{F}{A_o}\cos\lambda\cos\phi = \sigma\cos\lambda\cos\phi$$

- Plastic deformations in polycrystalline metals

- Strength and grain size are related by *Hall-Pelch equation:*

$$\sigma_y = \sigma_o + \frac{k}{\sqrt{d}}$$

- Nanocrystalline materials